Robust critical current density in applied magnetic fields in 5 μ m thick, SmBa₂Cu₃O_{7- δ} based superconducting wires

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Abstract

We report the magnetic field and temperature dependence of the critical current density $\{ J_c(H) \text{ and } J_c(T) \}$ flowing in a 5 μ m thick sample of SmBa₂Cu₃O_{7- δ} (SmBCO) film. The film is a coated conductor (CC) deposited on an IBAD-MgO textured metallic template. For a range of intermediate fields, we find $J_c \propto H^{-\alpha}$ with values of α between 0.44 and 0.49. These values are lower than those reported for other CC in the literature. The sample has a J_c of 13.6 MA/cm² at 5 K and self-field. Such high- J_c wires should find applications in large-scale energy applications of high-temperature superconductors. The temperature dependence of J_c at self-field and different applied fields is also analyzed.

Keywords: superconductors; coated conductors; magnetometer; ion beam-assisted deposition

1. Introduction

Since the discovery of high-temperature superconductors (HTS) nearly three decades ago, significant efforts have been devoted to understanding and modifying their properties. HTS are fascinating materials with great fundamental interest and significant technological potential, one of which is the development of tapes and cables for low loss conduction of high density electric currents. Issues arising from “weak-link” intergrain current transport have led to the development of different methods for their fabrication. The ion beam assisted deposition (IBAD) [1-3] method is one of the methods being used to create substrate on which highly textured HTS with low angle grain boundaries can conduct large intergrain

currents. This method involves the deposition of cubic metal oxide films to form substrates for the CC. Within the IBAD research community, there have been many different cubic metal and metal oxide materials that have been demonstrated to be biaxially textured to some degree. Two of these that were initially used as templates are yttrium-stabilized zirconia (YSZ) and gadolinium zirconate (GZO) [1,2]. More recently, a third template, magnesia (MgO) has been in use more frequently. The Stanford group that first developed IBAD-MgO explained that a key reason for its rapid texture evolution was its rock-salt structure [4,5]. The rolling assisted biaxially textured substrates (RABiTS) [6-8] and the inclined substrate deposition (ISD) [9,10] are the two other methods commonly used in the coated conductor industry for fabricating superconducting tapes.

To obtain a high critical current I_c , high J_c should be maintained over several micron thick films. Among the processes suggested for deposition of thick YBCO layers is electron-beam co-evaporation [11]. The SmBCO films used in this study are fairly thick (5.0 μm) and also display excellent cube-on-cube epitaxy over the entire thickness [12]. The films were deposited on IBAD-MgO template using the Evaporation using Drum in Dual Chamber (EDDC) process. We recently reported an exceptionally high I_c performance for these 5 μm thick wires, with average I_c over 1,000 A/cm-width for the entire 22 meter long wire and maximum I_c over 1,500 A/cm-width for a short 12 cm long tape [12]. These I_c values are the highest values ever reported from any lengths of cuprate-based HTS wire or conductor. No data was however provided in the previous work on in-field properties. In this paper, we report on a detailed study of the in-field superconducting properties of these thick films over a wide temperature – field space.

Good pinning properties are also desirable in superconducting films in order to obtain high J_c and to allow usage in electronic and power applications. From the J_c values obtained for this sample, we know that the vortex pinning forces is substantial and that the intrinsic pinning sites are very effective. Perhaps the most complex and poorly understood pinning enhancement mechanisms arise from replacement of yttrium in YBCO films with a light rare-earth (RE) element such as samarium (Sm) as done in this sample. Although it has been long known that such REBCO compounds show different and sometimes enhanced field-dependent J_c behavior compared with YBCO, the reasons for this are uncertain. However obvious influences are the increased transition temperature (T_c) values [13], and growth thermodynamics and kinetics that are thought to yield improved film microstructure [14].

2. Experimental

A 5 μm thick SmBCO coated tape was used in this study. The film is deposited on an IBAD-MgO template using co-evaporation method in Evaporation using Drum in Dual Chamber (EDDC) system. The composition of the sample is LaMnO_3 (LMO)/Epi-MgO/IBAD-MgO/ Y_2O_3 / Al_2O_3 /Hastelloy. A detailed description of the fabrication process is presented elsewhere [12]. For the magnetization measurements, we first mechanically sheared a sample of tape with dimensions of 3.58 mm by 3.81 mm. During the shearing process, some edge damage can result but this is unavoidable. The sample was mounted in a Quantum Design Magnetic Property Measuring System (MPMS-7) superconducting quantum interference device (SQUID) magnetometer equipped with a 7 T superconducting magnet. The J_c values were inductively (magnetically) determined by applying the modified critical state model [15-17] to the magnetic hysteresis via the relation:

$$J_c = \frac{20\Delta M}{a\left(1 - \frac{a}{3b}\right)}$$

This relation applies to a rectangular solid with field perpendicular to a face with sides $b > a$. Here, $\Delta M = M^- - M^+$ is the magnetic hysteresis, where $M^- (M^+)$ is the magnetization at temperatures T measured in decreasing (increasing) field H history. With these superconducting tapes in perpendicular field geometry, the flux density B can be replaced by $\mu_0 H$ to a close approximation. Fields in the range 0 - 6.5 T and in the c -direction were applied at different fixed temperatures (5 – 77 K) and the moment generated by the induced flowing current in the crystal was measured. In order to avoid field inhomogeneities, the scan length was set to 20 mm. Also, before beginning a measurement, the magnet was “reset” to eliminate any trapped flux and ensure that H was truly zero, and to provide a very quiet measurement environment. Signals of the reversible background magnetization from the ferromagnetic substrate were subtracted out before computing the J_c .

The superconducting transition temperature T_c for the sample was determined from temperature-dependent measurement of the magnetic moment in an applied field of 1 mT (10 Oe). The obtained onset temperature T_c is 92.25 ± 0.04 K.

3. Results and Discussion

Figures 1 and 2 show magnetization hysteresis loops (MHLs) of the SmBCO sample for H applied in the c -direction with fields up to 6.5 T. The shapes of the MHLs are highly symmetric and are typical of coated conductors. The symmetric property suggests that the bulk pinning is dominant [18]. This is in contrast to an asymmetric behavior which is usually observed in underdoped type-II superconductors. An asymmetric behavior suggests that the bulk pinning is small and that the influence of the surface barrier is important [19-20]. From the MHLs, we defined a field (H^*) where the two loops (obtained in decreasing and increasing field H history respectively) collapse into a single one. This H^* could be correlated with the irreversibility field H_{irr} for a superconductor. For the sample, H^* at 77 K is around 3.5 T and is close to 6.5 T at 65 K. However, we cannot estimate this value at lower temperatures due to equipment limitations.

Figure 1: Magnetic hysteresis loops of the SmBCO coated conductor in field parallel to c -axis at 5, 10, 20 and 27 K.

Figure 2: Magnetic hysteresis loops of the SmBCO coated conductor in field parallel to c -axis at 30, 40, 65 and 77 K

We next consider the field dependence of J_c at the various temperatures studied. Figures 3 and 4 show the logarithmic J_c vs. logarithmic H for the sample at various temperatures. Three factors that determine J_c in a magnetic field are the self-field value, the extent of the plateau at low fields, and the rate of decay beyond the plateau. We first look at the plateau region which is the region where vortex - pinning interactions are dominant over vortex - vortex interactions. This region extends from 0 T to about 0.2 T at the lower temperatures and to about 0.04 T at the higher temperatures. The average values for J_c at 5 K is 13.6 MA/cm², at 27 K is 7.4 MA/cm² while at 77 K is 1.1 MA/cm². These values stay constant within the range of the magnetic field stated above. The extension of the plateau to higher fields (especially at low temperatures) will delay the onset of decay of J_c .

Figure 3: Field dependence of the critical current density J_c at temperatures 5, 10, 20, and 27 K for the SmBCO coated conductor sample. From the slope of the lines (not shown on graph), we obtained the exponent α in $J_c \propto H^{-\alpha}$ in the intermediate field range.

Figure 4: Field dependence of the critical current density J_c at temperatures 30, 40, 55 and 77 K for the SmBCO coated conductor sample. From the slope of the lines (not shown on graph), we obtained the exponent α in $J_c \propto H^{-\alpha}$ in the intermediate field range.

A particularly interesting feature in the $J_c(H)$ data in Figures 3 and 4 occurs in the intermediate field range i.e. the region of decay of J_c with applied field beyond the plateau. Here, the current density falls off with a power law field dependence $J_c \propto H^{-\alpha}$ with exponent α ranging from 0.44 to 0.49 at various temperatures. These values for α for these *in-situ*, e-beam co-evaporation deposited films are lower than those obtained for *ex-situ* deposited YBCO films on textured substrates using the BaF₂ process [21]. For the *ex-situ* YBCO films on coated conductors, the α values range from 0.5 to 0.69 [21]. Typical values for Pulsed Laser Deposition (PLD) YBCO films are 0.5 – 0.6 while lower values of 0.2 have been reported only in films with artificial pinning sites [22]. Reducing the magnitude of value lessens the rate of decay. This shows that the present sample should have less fall-off in J_c as H increases. This is a very desirable result especially for technological applications of these wires in high field operations such as in motors and generators.

For more quantitative details on the J_c values, we look at Figure 5. This is a plot of $J_c(T)$ obtained at self-field and different applied magnetic fields. At self-field, the estimated value of J_c at 5 K is 13.67 MA/cm², 6.85 MA/cm² at 30 K and 1.14 MA/cm² at 77 K. The ratio $J_c(5\text{ K})/J_c(77\text{ K})$ is about 11.9 which is slightly higher than the 10.1 ratio that have been reported in the literature for most thick films [22]. Literature reports typically list measured values of J_c for films that are deposited on different substrates, made of different compositions and measurements done via other methods. For this reason, it is difficult to make a one-to-one comparison of J_c values in our sample with other CC of similar thickness. However, the robust J_c values translates to high I_c values which are the highest values ever reported from any lengths of cuprate-based HTS wire or conductor [12].

Figure 5: Temperature dependence of the critical current density J_c at self-field and various applied magnetic fields. The lines are fits to the experimental data. Equation for the fit is in the article.

Still on Figure 5, we analyze the temperature dependence of J_c . For all the J_c obtained, the curves are fitted well with an expression of the form $J_c = J_c(0) (1-T/T_c)^n$. For the self-field data, $J_c(0) = 14.8$ MA/cm² and $n = 1.75$. For the 3T data, $J_c(0) = 5.8$ MA/cm² and $n = 2.4$. The general trend noticed is that the value of n gradually increases as H increases. This implies a faster fall off (decay) of the J_c with respect to temperature at higher applied magnetic field H . This result is not unexpected for superconductors. We thus conclude that the dependence of J_c on temperature is similar at low and high fields but the decay is faster at higher fields. This result might also imply that we have slightly different pinning mechanisms at low and high applied magnetic fields in this sample.

4. Summary

We have reported the studies we made on a 5 μ m thick, SmBCO superconducting wire. The piece used in this work is part of a 22 m long wire that was deposited on an IBAD MgO substrate. The J_c were measured via magnetic induction in different applied fields and temperatures. This CC has a very high engineering critical current [12], a property that is desirable when making wires for use in high field operations such as in motors and generators. The alpha values which measures how fast the J_c falls off

with applied field are found to be lower (0.44 – 0.49) when compared to YBCO coated conductors that are made by various methods (0.5 – 0.69). Analysis of the J_c as a function of temperature show a faster decay at higher fields but overall we notice similar behaviors at low and high applied magnetic field.

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Figure Captions

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References

- [1] Y. Iijima, O. Tanabe, O. Kohno, Y. Ikeno, In-plane aligned $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin films deposited on polycrystalline metallic substrates, *Appl. Phys. Lett.* 60(6) (1992) 769.
- [2] Y. Iijima, K. Onabe, N. Futaki, N. Tanabe, N. Sadakata, O. Kohno, Y. Ikeno, Structural and transport properties of biaxially aligned $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ films on polycrystalline Ni-based alloy with ion-beam-modified buffer layers, *J. Appl. Phys.* 74(3) (1993) 1905.
- [3] R. P. Reade, P. Berdahl, R. E. Russo, S. M. Garrison, Laser deposition of biaxially textured yttria-stabilized zirconia buffer layers on polycrystalline metallic alloys for high critical current Y-Ba-Cu-O thin films, *Appl. Phys. Lett.* 61(18) (1992) 2231.
- [4] P. N. Arendt, S. R. Foltyn, Biaxially textured IBAD-MgO templates for YBCO-coated conductors, *MRS Bull.* 29(8) (2004) 543.
- [5] C. P. Wang, K. B. Do, M. R. Beasley, T. H. Geballe, R. H. Hammond, Deposition of in-plane textured MgO on amorphous Si_3N_4 substrates by ion-beam-assisted deposition and comparisons with ion-beam-assisted deposited yttria-stabilized-zirconia, *Appl. Phys. Lett.* 71(20) (1997) 2955.
- [6] A. Goyal, D. P. Norton, J. D. Budai, M. Paranthaman, E. D. Specht, D. M. Kroeger, D. K. Christen, Q. He, B. Saffian, F. A. List, D. F. Lee, P. M. Martin, C. E. Klabunde, E. Hatfield, V. K. Sikka, High critical current density superconducting tapes by epitaxial deposition of $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thick films on biaxially textured metals, *Appl. Phys. Lett.* 69(12) (1996) 1795.

[7] A. Goyal, R. Feenstra, F. A. List, M. Paranthaman, D. F. Lee, D. M. Kroeger, D. B. Beach, J. S. Morell, T. G. Chiravil, D. T. Verebelyi, X. Cui, E. D. Specht, D. K. Christen, P. M. Martin, Using RABiTS to fabricate high-temperature superconducting wire, JOM 51(7) (1999) 19.

[8] M. W. Rupich, U. Schoop, D. T. Verebelyi, C. Thieme, W. Zhang, X. Li, T. Kodenkandath, N. Nguyen, E. Siegal, D. Buczek, J. Lynch, M. Jowett, E. Thompson, J.-S. Wang, J. Scudiere, A. P. Malozemoff, Q. Li, S. Annayarapu, S. Cui, L. Fritzemeier, B. Aldrich, C. Craven, F. Niu, A. Goyal, M. Paranthaman, YBCO coated conductors by an MOD/RABiTS™ process, IEEE Trans. Appl. Supercond. 13(2) (2003) 2459.

[9] K. Hasegawa, H. Fujino, H. Mukai, M. Konishi, K. Hayashi, K. Sato, S. Honjo, Y. Sato, H. Ishii, Y. Iwata: Biaxially aligned YBCO film tapes fabricated by all pulsed laser deposition, Appl. Supercond. 4(10-11) (1996) 487.

[10] M. Fukutomi, S. Aoki, K. Kimori, R. Chatterjee, K. Togano, H. Maeda: Deposition of in-plane aligned $\text{YBa}_2\text{Cu}_3\text{O}_y/\text{Y}_2\text{O}_3$ stabilized ZrO_2 thin films on both sides of metallic tape substrates, Physica C 231(1-2) (1994) 113.

[11] V. Matias, J. Rowley, Y. Coulter, B. Maiorov, T. Holesinger, C. Yung, V. Glyantsev, B. Moeckly, YBCO films grown by reactive co-evaporation on simplified IBAD-MgO coated conductor templates, Supercond. Sci. Technol. 23(1) (2010) 014018.

[12] H.-S. Kim, S.-S. Oh, H.-S. Ha, D. Youm, S.-H. Moon, J.-H. Kim, S.-X. Dou, Y.-U. Heo, S.-H. Wee, A. Goyal, A ultra-high performance, high-temperature superconducting wires via cost-effective, scalable, co-evaporation process. Sci. Rep. 4 (4744) (2014) DOI:10.1038/srep04744.

- [13] J. G. Lin, C. Y. Huang, Y. Y. Xue, C. W. Chu, X. W. Cao, J. C. Ho, Origin of the R-ion effect on T_c in $\text{RBa}_2\text{Cu}_3\text{O}_7$, Phys. Rev. B 51(18), (1995) 12900.

- [14] C. Kwon, L. R. Kinder, Y. Fan, Y. Gim, A. T. Findikoglu, J. F. Bingert, J. Y. Coulter, S. R. Foltyn, D. E. Peterson and, Q. X. Jia, Improved superconducting properties of $\text{SmBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Films using $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ buffer layers, Phil. Mag. B 80(1) (2000) 45.

- [15] C. P. Bean, Magnetization of hard superconductors, Phys. Rev. Lett. 8(6) (1962) 250.

- [16] C. P. Bean, Magnetization of high-field superconductors, Rev. Mod. Phys. 36(1) (1964) 31.

- [17] A. M. Campbell, J. E. Evetts, Flux vortices and transport currents in type II superconductors, Adv. Phys. 21(90) (1972) 199.

- [18] H. Lei, C. Petrovic, Critical current density and mechanisms of vortex pinning in $\text{K}_x\text{Fe}_{2-y}\text{Se}_2$ doped with S, Phys. Rev. B 84(5) (2011) 052507.

- [19] M. Pissas, E. Moraitakis, D. Stamopoulos, G. Papavassiliou, V. Psycharis, S. Koutandos, Surface barrier and bulk pinning in MgB_2 superconductor, J. Supercond. Nov. Magn. 14(5) (2001) 615.

- [20] L. Zhang, Q. Qiao, X. B. Xu, Y. L. Jiao, S. Y. Ding, and X. L. Wang, Surface barrier and bulk pinning in MTG YBaCuO , Physica C 445-448 (2006) 236.

- [21] A. O. Ijaduola, J. R. Thompson, R. Feenstra, D. K. Christen, A. A. Gapud, X. Song,
Critical currents of *ex situ* $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films on rolling assisted biaxially textured substrates:
Thickness, field, and temperature dependencies, Phys. Rev. B 73(13) (2006) 134502.
- [22] S. R. Foltyn, L. Civale, J. L. Macmanus-Driscoll, Q. X. Jia, B. Maiorov, H. Wang, M. Maley,
Materials science challenges for high-temperature superconducting wire, Nature Mater. 6(9)
(2007) 631.